A Multilevel and Multiobjective Programming Model for the Hawaii Fishery: Model Documentation and Application Results

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ABSTRACT

Management of Hawaii's fisheries faces great challenges due to the rapid growth that has intensified competition among fisheries and users with different interests. This study develops and applies a multilevel and multiobjective programming model to assist decision-making in Hawaii's fishery. The multilevel aspect of the model incorporates objectives of both policy makers and fishermen. The use of a multiobjective model is essential in fisheries management since the typical fishery policy problem is characterized by more than one objective or goal that decision makers wish to optimize. The model covers nine fleet categories, five areas, four seasons, and 14 target species, of which 10 are target species. Catch per unit of effort (CPUE) includes targeted and bycatch species. A nonlinear relationship between CPUE and effort is incorporated into the model.

Under various objectives or policy options, the current model provides optimum solutions by fleet mix and its spatial and temporal distribution, as well as harvest level of fish resources. First, applications of the model indicate that economic efficiency of the Hawaii commercial fisheries can be improved if the number of handline vessels increases and the longline vessels would be more flexible in switching targets since the relative abundance of fish resources affects the choice on optimal fleet mix. Under profit maximization, optimal fleetwide profit could increase from the actual profit of \$4.5 million to \$17.96 million accompanied by 14% reduction in catch and 41% decrease in effort. Second, the multiobjective analyses showed that the degree of conflict between recreational and commercial fishing varies by effort level. At the current effort level, an increase of one recreational trip reduces commercial profit by \$12.14 where at lower levels of commercial effort. Moreover, the study concludes that the area closure regime has reduced the conflict between commercial and recreational fishing; however, it caused profit loss to the longline fishery in a range of \$0.70 to \$0.44 million.

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1. INTRODUCTION

1.1 Brief Background of Hawaii's Marine Fisheries

Marine fisheries have a long history in Hawaii, and they have economic and cultural significance to the State. Hawaii's marine fisheries are important to the State's economy because they contribute to the local seafood supply, employment, and income. Hawaii's commercial fisheries industry generated $63 million ex-vessel revenue from 32 million pounds of commercial landings in 1996 (NMFS 1997). In addition, there are three other direct components, recreational fishing, subsistence fishing, and charter fishing, which contribute the economic value to the Hawaii's marine fisheries (Pooley 1993). Fishing and fish production not only have economic significance, but perhaps more importantly, also have cultural significance in Hawaii. Traditionally, fish was one of the main foods of native Hawaiians. Seafood consumption is also popular among Asian ethnic groups. As a result of cultural adoption by the rest of the population, per capita seafood consumption in Hawaii is much higher than the national average. The mild and tropical climate, as well as short distance from shore to deep sea, makes Hawaii one of the world's finest recreational fishing grounds year-round. Fishing activities attract tourists to Hawaii and they also provide Hawaii's residents an important release from urban culture and an opportunity for traditionally subsistence fishing practices.

Hawaii fishers harvested various species by different fishing methods, which included longline, handline, troll, pole-and-line (aku), and other miscellaneous methods used primarily for inshore fishing. The longline pelagic fishery is the largest commercial fishery in Hawaii, valued at $47 million ex-vessel revenue in 1996. The small-scale troll and handline fisheries for pelagic fish are next in value, at $9 million ex-vessel revenue, while lobster, *aku* (skipjack tuna), and bottomfish are the other major commercial fisheries.

1.2 Research Objectives

During the last two decades, Hawaii's commercial marine fishery has experienced rapid growth and structural change. The dramatic development of the longline fishery contributed most to the growth. The rapid development of Hawaii marine fisheries brought with it significant biological, economic, as well as social impacts. Competition among fisheries and/or user groups with different interests for the limited resources has intensified, and consequently fisheries management faces great challenges in trying to balance the needs and interest of different groups while protecting the fisheries resources at the same time (Pan 1998).

In general, the central political issue facing the Hawaii fisheries management is how to balance all of these interests and to allocate the uncertain quantities of fish between segments of the fishery (Pooley 1993). Unfortunately, research regarding distributive issues in Hawaii fisheries is inadequate to support fisheries management (Skillman *et al.* 1993). Lack of quantitative measurement and analysis tools on the relative benefits and costs related to the various human components of the fisheries increases the difficulty of the decision-making process; thus, each regulation is undertaken with a high degree of uncertainty concerning its effect on the participants in the fisheries (Pooley 1993). Therefore, to improve fisheries management, an analytic tool is needed to evaluate impacts of management actions from the perspectives of the entire fisheries as well as the various sectors of the fisheries. Research methodologies used to reveal tradeoffs in terms of costs and benefits to the entire fishery, as well as to each individual segment under different management objectives or under different policy options, can be useful in determining the optimal policy for the Hawaii fisheries management.

Mathematical programming is an attractive approach for fisheries management because it is capable of solving a system problem such as fisheries management that has many decision variables, within a multiobjective and multilevel environment. While the computational difficulties hinder the use of the optimal control theory in empirical research and simulation often results in an unlikely optimal solution for fisheries management, the mathematical programming approach operates at a highly disaggregated level providing insights into system behavior. Hence, mathematical programming techniques provide a particularly useful methodology to study distributive and operational issues facing fishery management (Önal 1996, and Gunn *et al.* 1991). Therefore, they have been applied to fisheries modeling and have addressed such issues as effort allocation, fishery industry structure, regulation scheme and impact, and harvest strategy for decades.

In one application of the mathematical programming techniques, a linear programming model was developed for the Northwestern Hawaiian Islands (NWHI) fisheries both as a directed bottomfish fishery and as a multipurpose fishery (E.R.G. Pacific Inc. 1986, and Kasaoka 1989). This model is referred to NMFS LP hereafter. The initial intent of the NMFS LP model was to analyze the potential impact of the limited-entry program on various Hawaii fisheries and on the economic performance of various fishing fleets. However, this effort was not particularly successful (Pooley 1993). First, the results of a baseline run of NMFS LP model did not realistically depict the actual fisheries situation in Hawaii (Miklius and Leung 1990). The model developer provided the following explanations for the unrealistic solution (E.R.G. Pacific Inc. 1986). First, relationships in the model may not be linear. Second, vessels within each fleet group may not be homogenous with respect to their costs, catch rates and fishing capacities. And third, incidental catches (bycatch) are not modeled. More importantly, Miklius and Leung (1990), in an evaluation of the NMFS LP model, concluded that the omission of microlevel decision-making by the fishermen and the omission of the decision makers' objectives other than profit maximization contributed to the unrealistic solutions from the model. In addition, the typical fishery policy problem is characterized by more than one objective or goal that the policy makers wish to optimize. It is obvious that in order for any models to be useful for policy analysis, a multiple objective approach has to be undertaken (Leung *et al.* 1999).

Therefore, an appropriate modeling technique, which includes multiobjective and multilevel analysis, is needed to model the Hawaii fisheries system in order to assist the decision making process for the Hawaii fisheries management. Research has been done recently to develop and test a multilevel and multiobjective programming model for the Hawaii fishery (Leung *et al.* 1999, and Pan 1998). To illustrate the uses of the current model, the study applied the current model to analyze several issues that are associated with the management of the Hawaii fisheries (Pan 1988). The specific objectives of the model applications in this study were to:

1. estimate the impact of stock conditions;
2. assess the impact of declining CPUE;
3. evaluate the tradeoffs between recreational fishing and commercial fishing; and
4. estimate impacts of the area-closure regime on commercial fisheries.

1.3 Overview of the Report

The main purpose of this report is to elaborate the proceeding paper, which was presented in the 1997 conference on Ocean-Scale Management of Pelagic Fisheries: Economic and Regulatory Issues (Leung *et al.* 1999), to provide detail description on the structure of the current model. This paper also highlights the results and findings from the empirical applications of the current model. More detail information about the model development and the empirical applications, as well as the data sources that used for the applications, can be found in the dissertation of Minling Pan (1998).

Section 2 presents the structure and scope of the multilevel and multiobjective programming model for the Hawaii fishery. A detailed description on how to use formulations to reflect the complex reality of the Hawaii fishery is given in this section. Data sources are briefly discussed in Section 3. Section 4 illustrates the model applications, which employed the current model to analyze several issues associated with the Hawaii fisheries management. Finally, Section 5 presents conclusions and the potential uses of the current model.

2. A MULTILEVEL AND MULTIOBJECTIVE MODEL

2.1 Model Outline

A two-level multiobjective nonlinear programming model was developed for the Hawaii fishery in this study. Figure 2.1 gives a simple representation of the model and its related inputs and outputs. The model formulation allows fishery management to consider the behavior of individual fishermen as well as fishery managers (fleetwide). It also considers the importance of other management objectives such as recreational fishing and employment opportunities in addition to the profit-seeking commercial fishing activities. Under various objectives (goals) and/or policy options facing Hawaii's fisheries, the current model not only provides optimal solutions of effort and catch and their spatial and temporal distributions, but also can be used to evaluate the tradeoff between policy goals. Optimal solutions from solving the model can be viewed as the outputs of the model, while policy goals and instruments, as well as the parameters that represent biological, technological and economic conditions of the fisheries, can be viewed as inputs to the model. The presentation of the model in this chapter includes the three components in a mathematical programming model, namely decision variables, constraints, and objectives. The nature of a mathematical programming model is to search for the values of the decision variables that result in optimal values for the defined objectives under the constraints.

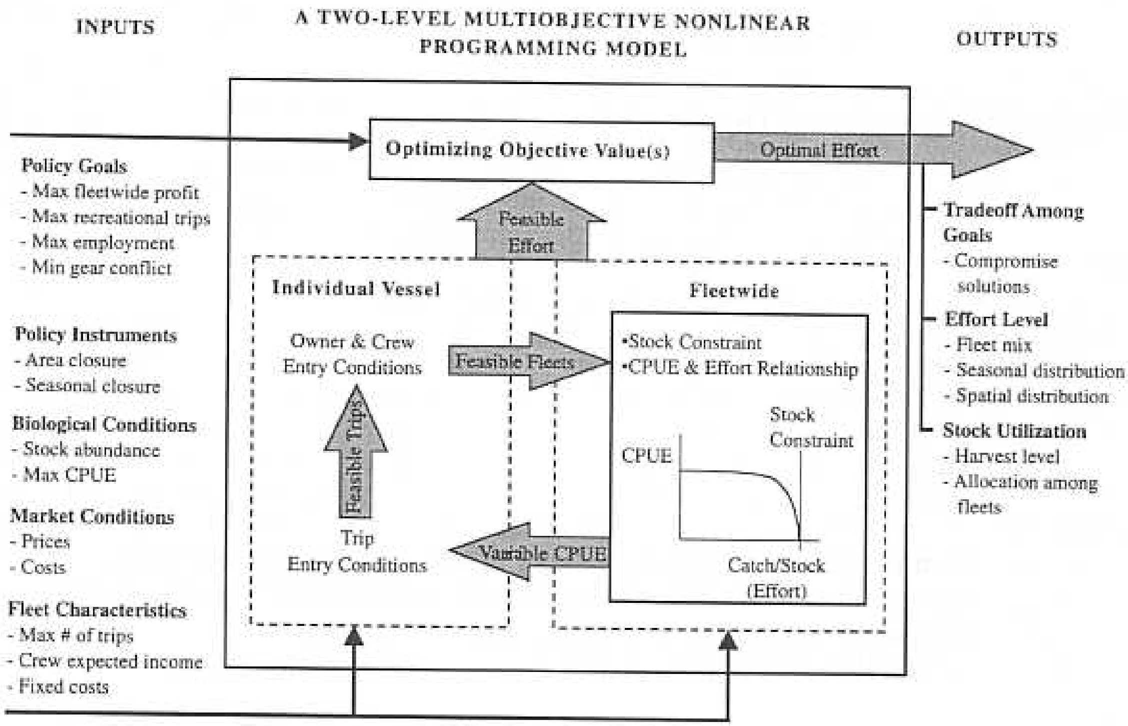


Figure 2.1 Model Structure and Mathematical Relationship Outline

2.2 Decision Variables

In accordance with traditional fishery economics research (Schaefer 1954, and Gulland 1968), fishing effort is specified as the decision variable in the current model. Fishing effort is an important decision variable in fishery management. In the United States, effort control—such as limited entry, seasonal or area closures, and effort quota—is a regular practice in fisheries management. Therefore, effort is an important decision variable in fisheries management.

In the current model, fishing effort is expressed in terms of the number of vessels in various fleets (fleet mix). The number of vessels in a specific fleet is associated with the number of trips taken by the fleet, because the number of trips taken by a vessel within a time period (year or season) is limited. Moreover, fishing effort is defined with four-dimensional variables encompassing fleet types, target species, area, and season, in order to reflect the variations in fishing activities of the Hawaii fisheries resulting from fishermen's motivation, vessel size, gear used, location of fishing grounds, and season. This model covers nine fleet categories, ten target types, five fishing areas, and four fishing seasons. In other words, fishing effort is disaggregated as a number of vessels (or trips) of a particular fleet targeting a specific species in a specific area during one specific season.

The following equations illustrate the relationship between number of trips and annual fleet size. The relationship between the number of trips and the number of vessels in four dimensions is represented by:

$$E_{ijkl} - \varepsilon_{ijkl} V_{ijkl} \leq 0 \qquad (1)$$

Seasonal fleet size is represented by:

$$V_{il} - \sum_{j} \sum_{k} V_{ijkl} \geq 0 \qquad (2)$$

Annual fleet size is represented by:

$$V_i - V_{il} \geq 0 \qquad (3)$$

where:

Variable indices:

- i = fleet, $i = 1, \ldots, 9$;
- j = target species, $j = 1, \ldots, 10$;
- k= area, $k = 1, \ldots, 5$;
- l = season, $l = 1, \ldots 4$.

Variables:

- E_{ijkl}: number of trips of fleet i targeting j in area k during season l (trip);
- V_{ijkl}: number of vessels of fleet i targeting j in area k during season l (vessel);
- V_{il}: number of vessels of fleet i during season l (vessel);
- V_i: annual fleet size of fleet i (vessel).

Parameters:

- ε_{ijkl}: maximum number of trips for a vessel in fleet i target species j in area k during season l (trip/vessel).

Equation $E_{ijkl} - \varepsilon_{ijkl}V_{ijkl} \quad 0$ represents the limitation of the maximum number trips a vessel takes in a season (ε_{ijkl}). The number of trips is limited due to the constraints of holding capacity of vessel, shelf life of the harvested species, distance to the fishing ground, and length of season. Therefore, the maximum-number-of-trips vary by fleet, target, fishing ground, and season.

The number of active vessels (fleet size) can be varied by season, in order to depict the seasonal variation of fishing activities of each individual fleet. The seasonal fleet size (V_{il}) is defined as the aggregated number of vessels over different target species (j) in various areas (k) during the season (l). This relationship is expressed mathematically in Equation (2) as: $V_{il} - \sum_{j}\sum_{k} V_{ijkl} \geq 0$.

The equation of $V_i - V_{il} \geq 0$ represents that annual fleet size (V_i) which is defined as the largest fleet size among the four seasons of fleet i. This formulation accounts for annual fixed costs as long as the vessel is active in any one season. This is one of the improvements that the current model offers over the NMFS LP model. The NMFS LP model charges vessel fixed cost by season and thus is unrealistic since the fishermen have to bear the annual fixed costs for the active seasons as well as the inactive ones.

2.2.1 Fleet Categories

Fleet classification is necessary because this study is involved with multiple fisheries and heterogeneous fishing fleets. The fishing fleets are classified into nine categories based on fishermen's motivation, gear type, and vessel size. Vessels within a fleet are assumed to be homogenous. Figure 2.2 illustrates the classification of the nine fleets and Table 2.1 summarizes their characteristics. This specification attempts to include the three major fisheries (pelagic, bottomfish, and lobster) and the different style fishermen including commercial, semi-commercial, and recreational fishermen in the Hawaii fishery. The actual numbers of vessels of these nine fleets in the Hawaii fishery are also presented this table.

The fleets are divided into two major groups, namely non-commercial and commercial fleets, based on whether or not fishing is an income source to the fishermen. Furthermore, the non-commercial group is divided into two fleets, namely recreational and *expense*, based on the disposition of catch. The commercial group is classified into seven fleets, which include charter boats, commercial handliners, commercial trollers, small multipurpose vessels, medium multipurpose vessels, large multipurpose vessels, and aku (pole-and-line) boats.

Recreational fleet refers to the fishing vessels involved in fishing activities without any catch sale. Among the 575 small-boat fishermen surveyed in 1996, about 28% fished for recreation and did not sell any catch (Hamilton and Huffman 1997). The other category of recreational fleets, named as *expense*, refers to a group of small-boat fishermen who sell at least part of their catch, but the revenue from fish sale does not cover all their expenses. In Hawaii, there were significant numbers of small-boat fishermen who sold at least part of their catch, but who do not consider themselves to be commercial fishermen. The current model considers the expense fishermen to be recreational users, as these vessels are not using the fisheries for strictly commercial purposes. According to the small-boat survey (Hamilton and Huffman 1997), earnings of expense fishermen were far less than break even.

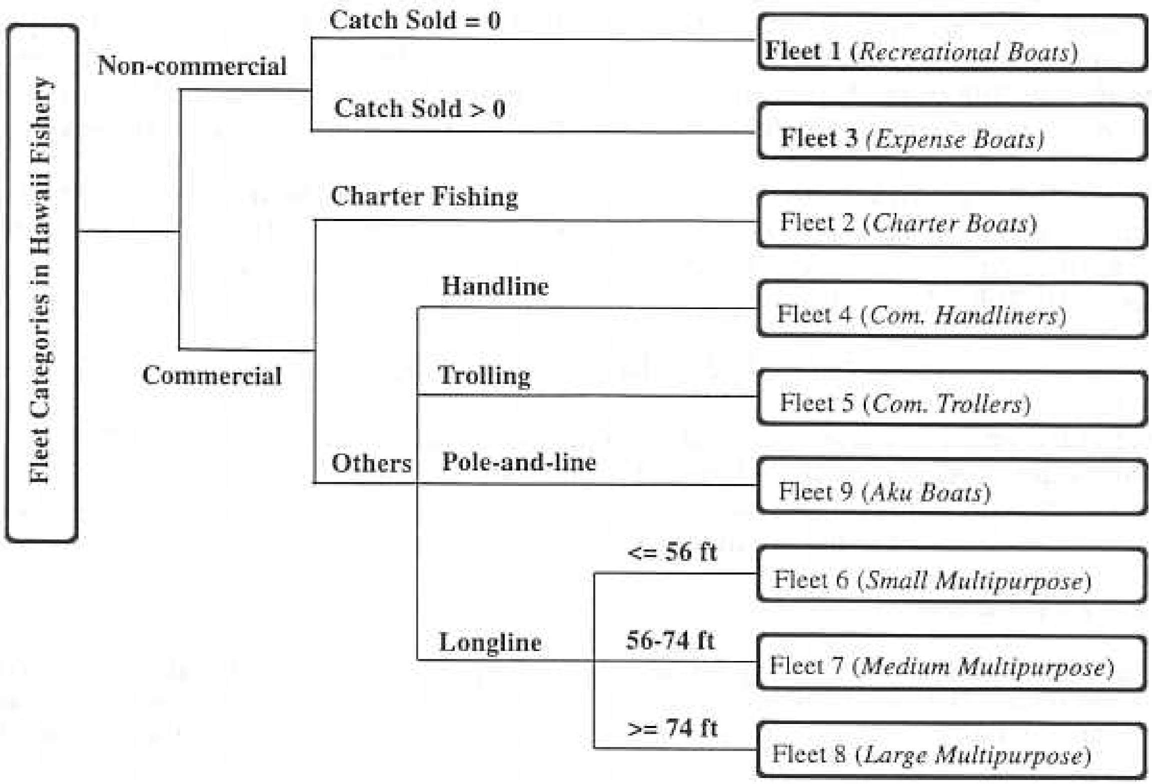


Figure 2.2 The Fleet Categories of the Hawaii Fishery

Table 2.1. Fleet Categories and their Main Characteristics

Fleet (i)	Main gear	Avg. vessel length (feet)	Catch disposition	Income source	No. of vessels 1993[a]	Catch 1993[a] (1000 lb)
Noncommercial						
1. Recreational boats	Troll or handline	20	Keep or share	No income	2,490	1,412
3. Expense boats	Troll or handline	23	Sell part	No income	952	3,185
Commercial						
2. Charter boats	Troll or handline	36	Sell part or all	Main source	99	1,105
4. Com. Handliners	Handline	25	Sell most or all	Main or part	149	4,756
5. Com. Trollers	Troll	25	Sell most or all	Main or part	232	3,060
6. Small Multipurpose	Longline	<54	Sell all	Main source	30	3,113
7. Medium Multipurpose	Longline	54-74	Sell all	Main source	48	7,538
8. Large Multipurpose	Longline	>74	Sell all	Main source	44	8,605
9. Aku Boats	Pole-and-line	60	Sell all	Main source	8	2,332

[a] Data sources for the actual number of vessels and catch for each fleet of the Hawaii fishery in 1993 are presented in Chapter 4.

Seven commercial fleets were identified in the current model. Fleet 2 refers to charter boats on which patrons pay to fish for recreational purpose, while the boat operators intend to make a living from patrons' payment and selling fish caught. Hence, charter boats were defined as a commercial fleet in the current study. Fleet 4 represents the commercial handline vessels where fishermen use handline gear and expect to earn a certain amount of their income from fishing activities. This fleet involves both pelagic and bottomfish fisheries. The commercial trolling fleet (Fleet 5) participates in pelagic fishery using trolling gear and the fishermen of this fleet expect at least positive income from their fishing activities. Fleet 9 represents aku boats or bait boats in the Hawaii fisheries, which use the pole-and-line method to target aku. Historically, the pole-and-line fishery was the largest commercial fishery in Hawaii. Despite the fact that it had substantially declined, aku boats still harvested 17.5% of the total tuna landed in Hawaii pelagic fishery in 1993 (the base year of this study) (WPRFMC 1994a). Fleets 6, 7, and 8, the small, medium, and large multipurpose fleets, respectively, represent the vessels equipped with longline gear and other gear types. They are multipurpose fleets because they are capable of adding other fishing gears without removing the main part of longline gear. For example, by removing part of the longline fishing equipment, such as floats, lines and hooks, a longline vessel can install the trap-haul equipment needed to catch lobsters within two to three weeks. The deepsea handline gear can be added to a longline vessel to target bottomfish. In fact, some vessels in the Hawaii fisheries have both a longline license and a bottomfish license, or a lobster license, and they may switch from one fishery to another fishery in different seasons. Fleets 6, 7, and 8 are classified based on their vessel length. The vessel size categories are consistent with the cost-earnings study of the Hawaii longline fleets conducted in 1993 (Hamilton *et al.* 1996).

2.2.2 Target Species (Trip Types)

Target is specified as one dimension of the decision variables, because choosing a species to target is a fishing strategy adopted by the fisherman. Target is associated with fishing behaviors, such as gear used, area, capture time, and depth fished, and it is also associated with outcomes such as CPUE and fish prices received (Boggs 1992a). In the Hawaii fishery, some species, such as yellowfin, are targeted by different fishing methods including handline, trolling, and longline gears. On the other hand, the same fishing method can target various species. Fishermen may switch targets during different seasons according to a change in fish abundance. Most of the fishermen do not change their targets during a trip. To simplify the model, this study assumes that each trip has only one target species or target type, and fishermen do not switch target during a trip.

A study by He *et al.* (1996) found that some longline fishermen appeared to switch fishing strategies (by set) within a trip if fishing efforts were identified into five types (clusters) based on catch composition. However He's study indicated that most of the longline trips appeared to reflect similar fishing strategies within a single trip. Trip type or trip target defined in the current study is a general concept that is not only evaluated by fish composition but also by fishing techniques. For example, longline trips are categorized by NMFS into only three categories, i.e., swordfish, tuna, and mixed, and fishermen identified the trip type for each trip in the NMFS logbook according to these three categories.

A fish species becomes the fishermen's target usually due to its high value and its abundant stock. Commercial fishermen and recreational fishermen may value a fish species in different ways. Commercial fishermen target species that bring higher profitability and income to their fishing operations, which may be a function of not only fish prices but also CPUE. Recreational fishermen may target fish species that bring greater sporting satisfaction without as much attention to marginal costs. For example, blue marlin is not a targeted species of the commercial fishermen because of its relatively low price in the Hawaii fish market. However it is a major targeted species of Hawaii's recreational fishermen. In the Hawaii fisheries, yellowfin, bigeye, skipjack (aku), swordfish, blue marlin, mahimahi, ono, bottomfish, and lobster are commonly targeted by different groups of fishermen. Some longliners practice a fishing method used to target both bigeye and swordfish, and that is referred to as the mixed target. The possible targets for each fleet are presented in Figure 2.5.

In Hawaii fisheries, it is common that fishermen catch not only the targeted species, but also significant amounts of untargeted species (bycatch) on each trip. Bycatch are sold to the market as soon as they have market value in Hawaii. Therefore, CPUE in this study is defined as a composite of the targeted species and bycatch. The detail definition of CPUE will be discussed in later part of this chapter.

2.2.3 Fishing Grounds (Areas)

The fishing grounds of Hawaii fisheries extend from just a mile offshore to over a thousand miles offshore. In Hawaii, small boats are scattered in all the Main Hawaiian Islands (MHI) fishing within 200 nmi, but mostly within 20 nmi. Longline fishing boats and lobster and bottomfish fishing boats can go beyond 200 nmi, and most of these vessels port in Honolulu.

The physical constraints of vessels, such as fuel capacity and vessel length, can limit the mobility of the fishermen. Fishermen's fishing motivation may also influence the areas that they prefer to fish in. The spatial variations in the abundance of fish resources have important impacts on catch composition. Also, the distance to fishing grounds will affect fishing costs and prices of fish caught. The current regulations for fisheries management in Hawaii are differentiated by fisheries as well as by areas. Therefore, to consider the spatial variations in Hawaii fisheries, for this model the fishing ground is divided into five areas based on the distance to the fishing ground. The distances between the five areas are shown in Table 2.2. Figure 2.3 shows Areas 1 to 3 that cover the areas originated from all of the MHI, while Figure 2.4 shows Areas 4 and 5 that cover the areas originated from the Oahu Island and Figure 2.5 shows the possible spatial distributions and the main targets of the nine fleets in the Hawaii fisheries.

Table 2.2. Area Classifications

Area (k)	Distant from Origin (nmi)	Origins
1	<=20	Main Hawaiian Islands
2	21-75	Main Hawaiian Islands
3	76-200	Main Hawaiian Islands
4	200-900	Oahu Island
5	900-2000	Oahu Island

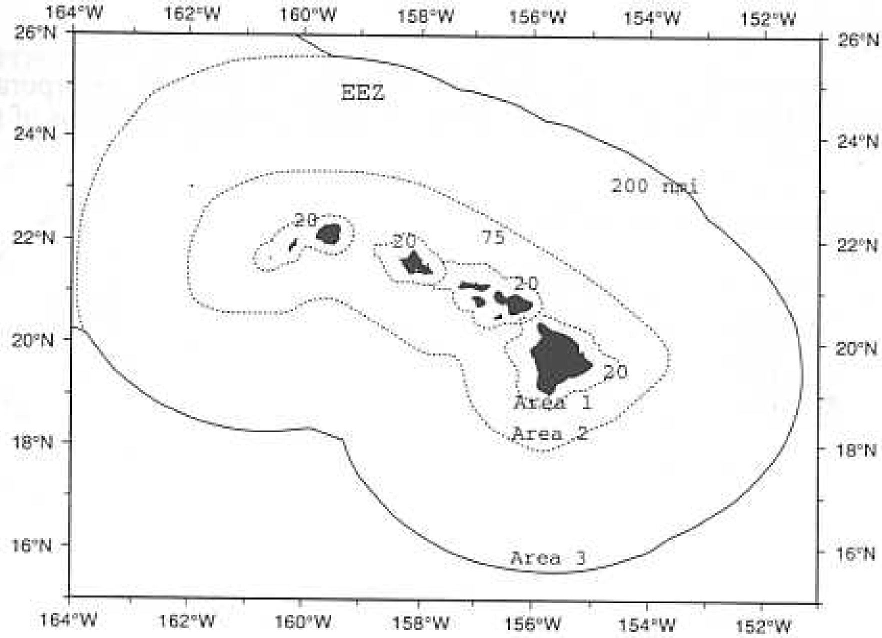


Figure 2.3 Map of the Areas 1, 2, and 3[1]

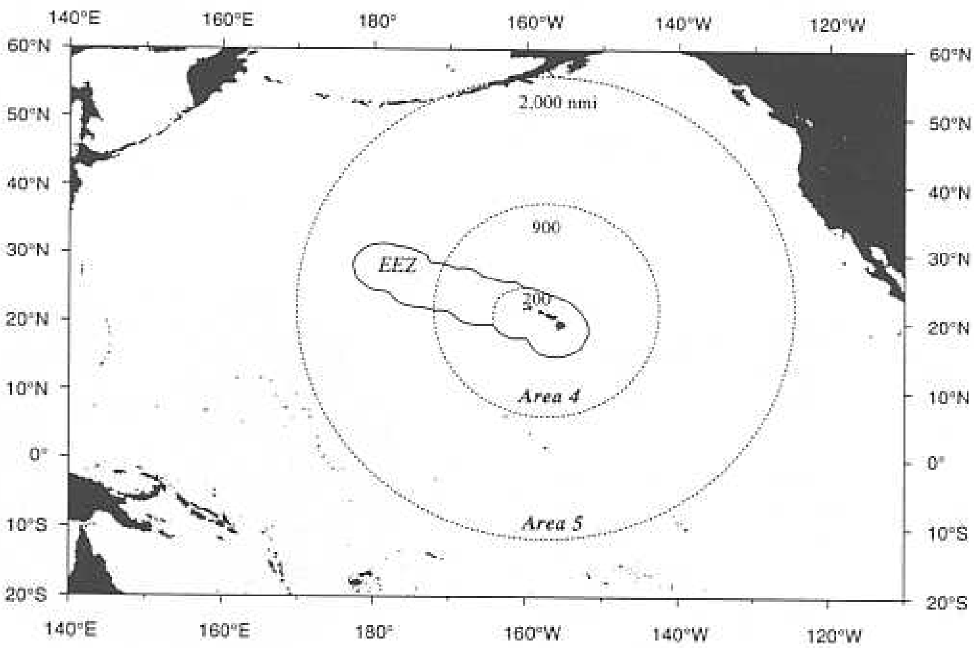


Figure 2.4 Map of the Areas 4 and 5

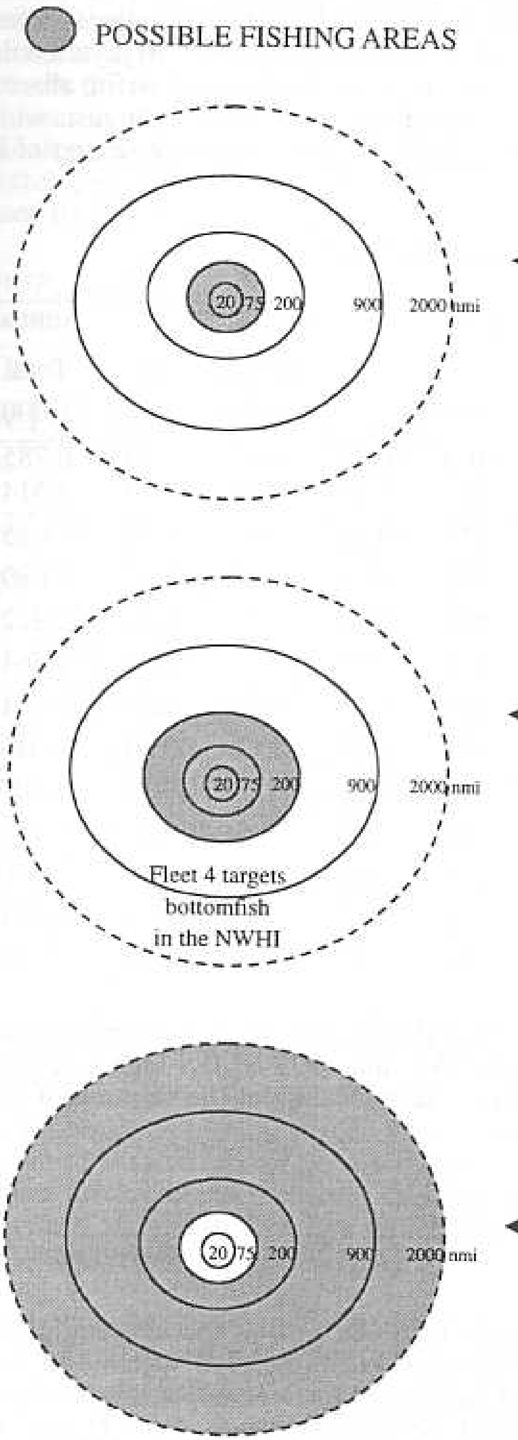
[1] Figures 2.3 and 3.4 are adapted from the maps provided by D.R. Kobayashi of the NMFS, Honolulu Laboratory.

2.2.4 *Fishing Seasons*

Four seasons are specified in the model (Table 2.3), in order to incorporate the seasonal variations of abundance of the important species and the seasonal variations of fishing activities in the Hawaii fishery.

Table 2.3. The Season Classifications

Season (l)	Period	Length (days)
1	Nov-Jan	90
2	Feb-May	120
3	Jun-Aug	90
4	Sept-Oct	60



TARGETING SPECIES

Fleet 1 (*Recreational Boats*)
1) mixed

Fleet 2 (*Charter Boats*)
1) yellowfin 2) skipjack 3) blue marlin 4) mahimahi 5) ono 6) bottomfish 7) mixed

Fleet 9 (*Aku Boats*)
1) skipjack

Fleet 3 (*Expense Boats*)
1) mixed

Fleet 4 (*Commercial Handliners*)
1) yellowfin 2) bigeye 3) bottomfish (Area 1-5) 4) mixed

Fleet 5 (*Commercial Trollers*)
1) yellowfin 2) blue marlin 3) mahimahi 4) ono 5) mixed

Fleet 6 (*Small Longliners*)
1) yellowfin 2) bigeye 3) swordfish 4) bottomfish 5) lobster 6) mixed

Fleet 7 (*Medium Longliners*)
1) yellowfin 2) bigeye 3) swordfish 4) lobster 5) mixed

Fleet 8 (*Large Longliners*)
1) yellowfin 2) bigeye 3) swordfish 4) mixed

Figure 2.5 Current Possible Fishing Areas and Target Species of the Fleets

The volumes of landings for most of pelagic species varied seasonally. Table 2.4 illustrates the average volumes of landings in the four seasons from 1990 to 1995 for the major species landed in Hawaii. The bolded number indicates the peak season for a species. Bigeye landings was peak in the season from September to October. Some species, such as yellowfin, albacore, aku, blue marlin, and lobster, had their peak season of landings from June to August, while some species, such swordfish, striped marlin, mahimahi, and ono, had their peak season of landings from February to May.

Table 2.4 The Average Seasonal Landings from 1990-1995[a]

	Nov-Jan		Feb-May		Jun-Aug		Sept-Oct		Annual
Species	pound (1,000)	%	pound (1,000)	%	pound (1,000)	%	pound (1,000)	%	Total (1,000)
Yellowfin	860	0.13	1,878	0.28	3,103	**0.46**	943	0.14	6,785
Bigeye	1,745	**0.39**	1,582	0.35	657	0.15	530	0.12	4,514
Albacore	317	0.22	324	0.22	553	**0.38**	250	0.17	1,445
Swordfish	563	0.09	3,770	**0.62**	1,517	0.25	239	0.04	6,089
Blue Marlin	468	0.17	658	0.23	1,095	**0.39**	600	0.21	2,822
Striped Marlin	478	0.31	561	**0.36**	329	0.21	194	0.12	1,561
Mahimahi	439	0.21	718	**0.34**	481	0.23	482	0.23	2,121
Ono	118	0.11	438	**0.42**	359	0.34	132	0.13	1,046
Aku	668	0.22	704	0.23	1,113	**0.36**	622	0.20	3,107
Shark	45	0.24	71	**0.38**	46	0.25	25	0.13	187
Other Pelagic	257	0.26	356	**0.37**	219	0.23	138	0.14	970
Bottomfish	380	0.29	406	**0.31**	276	0.21	235	0.18	1,298
Lobster	11	0.12	25	0.27	44	**0.48**	31	0.34	92

[a]The landings refer to the commercial and recreational landings. The commercial landings are based on the fishermen catch report from 1993 HDAR and 1993 NMFS logbook; recreational landings were estimated and included in this table. The estimation of the volumes of landings is discussed in Chapter 4.

2.3 CPUE and Catch Components

2.3.1 The Definition of CPUE

In this study, CPUE (catch per unit effort) refers to total catch of all species caught per fishing day. On line with the definition of fishing effort as a four-dimension variable in the current model, CPUE (including the volume and components) varies by fleet, target, area, and season.
First, CPUE is defined as a composite of targeted catch and bycatch, since Hawaii's pelagic fishery, bottomfish fishery, and lobster fishery are all multispecies fisheries. Except for the lobster fishery that harvested only two species, spiny lobster and slipper lobster, both the pelagic fishery and the bottomfish fishery land more than ten species each. These fisheries, especially the pelagic fishery, are technologically interdependent, which means the harvest of one species can lead to the harvest, intentional or not, of another species. When a fisherman targets one of these species, they usually catch the targeted species as well as the other species simultaneously. However, a species that is bycatch in one fishery can be the direct catch of another fishery. For example, blue marlin is a bycatch of the longline fishery, but it is a main target species of the

recreational fishing. Such technological interdependent fisheries may result in conflict between different fishing activities. Therefore, the definition of CPUE in this study allows the model not only to account for total catch from all the fishing activities, but also to consider the bycatch problems in the Hawaii fisheries. The model includes 14 species or species groups including all the species caught and landed by Hawaii based fishing vessels. Nine species are categorized individually and the others are grouped into five species groups as shown in Table 2.5. CPUE (total catch per fishing day in this study) can be any combination of the 14 species and it can be expressed by the following formulation:

$$CPUE_{ijkl} = \sum_{s=1}^{14} R_{ijkls}$$

where:

$CPUE_{ijkl}$: total catch per fishing day for effort E_{ijkl}
R_{ijkls}: catch per fishing day of species s for effort E_{ijkl}.

Table 2.5. Species or Species Groups Included in the Model

Species (s)	Common Name	Species Group	Targeted Species (j)
1	Yellowfin	Pelagic	Yes
2	Bigeye	Pelagic	Yes
3	Albacore	Pelagic	No[2]
4	Skipjack	Pelagic	Yes
5	Swordfish	Pelagic	Yes
6	Blue Marlin	Pelagic	Yes
7	Striped Marlin	Pelagic	No
8	Mahimahi	Pelagic	Yes
9	Ono	Pelagic	Yes
10	Sharks	Pelagic	No
11	Other pelagic	Pelagic	No
12	Bottomfish	Bottomfish	Yes
13	Lobster	Lobster	Yes
14	All others	Miscellaneous	No

The individual species include four tuna species (yellowfin, bigeye, albacore, and aku), three billfish species (blue marlin, striped marlin and swordfish) and two other species (mahimahi and ono). Bottomfish and lobster are also important species in Hawaii fisheries. Because bottomfish and lobster are localized resources and the fishing method and CPUE are similar within each species group, specific bottomfish and lobster are represented by an aggregated species group of bottomfish and lobster respectively.

Sharks are included in the model because sharks make up a large percentage of the catch of the longline (37% of the total number of fish caught in 1993), although, because most of the bulk of shark catch are discarded at sea, a very small portion of the total sharks caught was landed[3]. The other pelagic species, such as spearfish (*T. angustirostris*) and black marlin (*M. indica*), are aggregated into a single category referred to as 'other pelagic'. Other miscellaneous species are grouped as "other species". This species group is landed primarily by other miscellaneous gears and included in the study because there are bycatch species for some fishing practices considered in the model.

[2] A few vessels (longline and handline) occasionally target albacore.
[3] Most of the shark value in Hawaii is at-sea processed fins, with the rest of the shark discarded at sea. However information on the value of shark for landings is very limited.

2.3.2 The Constant vs. Variable Catch Rate

The current study assumes two possible relationships between CPUE and effort, which are constant catch rate (CCR) and variable catch rate (VCR), shown in Figure 2.6. If a nonlinear relationship between catch and effort is assumed, CPUE is a set of variables in the current model. Otherwise, CPUE is a set of parameters of the current model.

Many studies suggest that intensive local fishing pressure can reduce CPUE in a local area, without affecting abundance of the stock as a whole (Gulland 1968, Sathiendrakumar and Tisdell 1987, and Curran *et al.* 1996). It is possible that local CPUE declines for pelagic species while effort increases and the catch approaches the rates of fish immigration and recruitment in a limited area (Boggs 1992b). Sathiendrakumar and Tisdell (1987) define local CPUE as a function of total local catch, based on the assumption that local CPUE reduces as total catch increases. Unfortunately, no empirical estimation of the relationship for pelagic species between CPUE and catch has been established (Boggs 1992b). A time series study on the Hawaii pelagic fisheries from 1962 to 1992 reported that no statistically valid relationship between catch rates and expanded fishing effort exists (He and Boggs 1995), and the impact of further increase in fishing effort in Hawaii's fisheries is unknown. However, it is useful to consider such relationships. Therefore, the current study assumes two possible relationships (CCR and VCR) between CPUE and effort.

Overall, the CCR model contains about 508 decision variables, and the VCR model contains about 7,000 decision variables since CPUE becomes a set of variables.

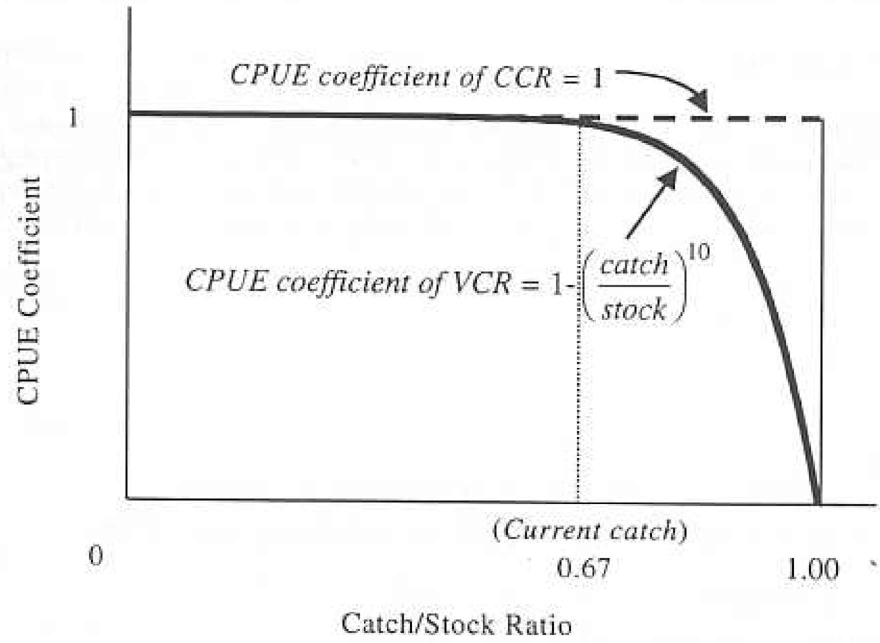


Figure 2.6 The Relationship between CPUE and Effort

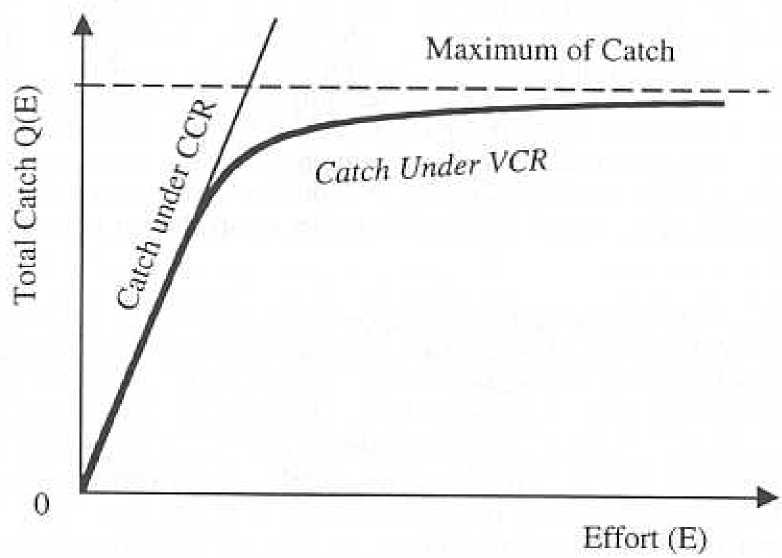


Figure 2.7 The Relationship between Catch and Effort

2.4 Fleetwide Constraints

2.4.1 Stock Constraints

During one season, the total catch in a limited area can not exceed the estimated fish stock in that area and for that season. The total catch of individual species is found by aggregating catch from targeted catch and bycatch over all fleets, to incorporate technological inter-dependence among stocks. The mathematical relationships of stock constraints are expressed in the equation below:

$$\sum_{i}\sum_{j} d^{f}_{ijkl} R_{ijkls} E_{ijkl} \leq s_{kls} \qquad (4)$$

where:

Variables:

R_{ijkls}: catch rate of species s for effort (trip type) E_{ijkl} (lbs/day);

E_{ijkl}: number of trips of fleet i target j in area k during season l (trips).

Parameters (constants):

d^{f}_{ijkl}: trip fishing days for effort E_{ijkl} (days/trip);

s_{kls}: stock for species s in area k during season l (lbs).

The stock of each species is specified as the total exploitable amount of fish (or total available catch) in the exploited areas of the Hawaii fisheries. However, the size of exploitable stocks of most species caught by Hawaii based vessels were difficult to determine. First, pelagic fish are highly migratory. Variations in the distribution and abundance of these pelagic species are often related to differences in their life history profiles, migration patterns, and habits that are affected by ever-changing environmental influences (WPRFMC 1995). Second, Hawaii fisheries have expanded both in size and in fishing grounds in the past two decades. Therefore, this study used the actual catch to estimate the total amount of exploitable catches for Hawaii fisheries. It was assumed that the exploitable stocks for the 14 species or species groups were at least as great as the actual catch.

The dynamic impacts of fish mortality are not considered in this model; thus it is a static model. For bottomfish and lobster fisheries, whose stocks are related to the reproduction and growth of resident fish, the current model represents short-run fishery behavior. However, for the Hawaii pelagic fisheries, the current model can represent short-run as well as long-run fishery behavior in terms of the biological concept. Because total pelagic catches by Hawaii fisheries comprise only a small fraction of Pacific-wide fisheries, catches from Hawaii fisheries are unlikely to cause a stock effect and the consequential reduction of pelagic fish abundance stock-wide. It would appear that the local fishing effort of the Hawaii fisheries is too small to have any significant effect on the size of stocks or their levels of production. For such a fishery, the local catch may increase with effort toward an asymptote (Skillman, *et al.* 1993, and Boggs 1992b).

2.4.2 *The Effort and CPUE Relationship*

These two different relationships between CPUE and effort result in different catch and effort relationships where catch increases as effort increases at various rates, as shown in Figure 2.7. The assumed function representing the possible relationship between CPUE and aggregated catch under VCR is expressed mathematically in the following equations:

$$A_{kls} = 1 - \left(\frac{Q_{kls}}{s_{kls}}\right)^n = 1 - \left(\frac{\sum_i \sum_j d^f_{ijkl} R_{ijkls} E_{ijkl}}{s_{kls}}\right)^n \quad (5)$$

$$R_{ijkls} = A_{kls} \overline{R}_{ijkls} \quad (6)$$

where:

Variables:

- A_{kls}: daily catch rate coefficient, whose value can be 1 to 0 depending on the ratio of total catch to stock s_{kls};
- Q_{ksl}: total catch of species s in area k and season l (lb);
- R_{ijkls}: daily catch per fishing day of species s for fleet i targeting species j in area k during season l (lb/day);
- E_{ijkl}: number of trips of fleet i target j in area k during season l (trips).

Parameters:

- s_{kls}: stock of species s in area k and season l (lb);
- $\overline{R}_{ijkls}$: the max catch per fishing day (lb/day);
- d^f_{ijkl}: number of fishing days per trip for effort E_{ijkl} (days/trip).

It is assumed that each type of effort is associated with a specific initial value of CPUE, and the initial (or maximum) CPUE for specific species ($\overline{R}_{ijkls}$) is determined by the stock-wide abundance condition. In this study, the initial value of CPUE was generated based on 1993 empirical data. Then, a coefficient (A_{kls}), whose value ranges from 1 to 0, is used to represent the degree of decline of CPUE. A coefficient of CPUE of 1 implies CPUE is at the maximum level, while a coefficient of CPUE of 0 implies CPUE reduces to zero. The actual CPUE value is determined by its initial value, which is associated with specific effort type (E_{ijkl}), and the coefficient value (Equation 6), which is associated with the total catch of a species.

The rate at which CPUE diminishes is dependent on the value of n in equation (5), given the fixed amount of stock s and total catch Q. The curve where n has a value of 10 represents that CPUE does not significantly decline until the point where the catch to stock ratio equals 0.667. Therefore, the curve where n equals 10 is chosen to represent a possible CPUE diminishing curve.

The CCR model assumes that the current effort has no negative effects on CPUE, and that a continuous increase in effort will not have any negative effects on CPUE. The coefficient of CPUE is equal to 1 and CPUE remains at the maximum for any effort level. Total catch increases proportionally to the effort increase. On the other hand, the VCR model presumes a nonlinear relationship between effect and total catch. Since no empirical estimation of the relationship between CPUE and catch has been established, nor has an estimate of local stock relationship between CPUE and catch has been established, nor has an estimate of local stock abundance been reported, the exploitable stock for Hawaii fisheries is assumed to be 50% more than the current catch, then the current catch (Q) to stock (s) ratio equals 0.667. As Figure 2.6 illustrates, from little effort up to the current effort level (where catch to stock ratio equals 0.667 if it is assumed that current catch is about 66.7% of the available stock), the crowding out effect may be too small to result in a significant decline of CPUE. However, when fishing effort exceeds the current level, CPUE declines at an increasing rate.

When the variable catch rate (VCR) is incorporated into the model, the model becomes a nonlinear programming model. As a result, fleetwide profit is nonlinear and it increases at the beginning when effort level is low, but eventually declines.

2.5 Mircolevel Entry Conditions

As discussed earlier, the NMFS model omitted microlevel decision-making by fishermen and consequently resulted in an unrealistic solution. First, fishery policy makers' objectives are typically not consistent with fishermen's objectives. For example, in fishery economic research, it is usually assumed that a commercial fisherman maximizes profit at the microlevel. However, at the macrolevel, improving economic efficiency of the fisheries is only one of the many objectives that fishery decision-makers try to achieve.

Second, maximizing fleet-wide profit does not necessarily imply maximizing individual fishermen's profit, especially when CPUE diminishes as effort increases. If CPUE declines as effort increases, an individual vessel's profit declines monotonically as total catch increases.
Third, in some fisheries, such as the Hawaii fisheries, there are diverse interest groups. As discussed earlier, Hawaii fishermen were categorized into nine fleets differentiated by motivation, vessel size, and fishing style. Different groups (fishermen) have various objectives or expectations from fishing.

Ideally, the two-level problem should be solved through the optimization at the fishermen's level nested within the optimization at the fishery managers' level. However, there is no practical solution algorithm for such a nested hierarchy model particularly given the nonlinear nature of the current model (Önal 1996). In order to keep the model manageable and solvable, the optimization at the fishermen's level is approximated by a set of entry conditions in this study. In other words, it was assumed that fishermen would make their decision to enter and continue fishing depending on certain conditions or expectations. These entry conditions include trip entry condition, crew entry condition, and owner entry conditions.

Due to lack of research on individual fishermen's behavior in the Hawaii fisheries, the parameters of these entry conditions were assumed to be varied by fleets and they were generated based on the empirical data of the Hawaii fisheries. The amount of trip costs and the percentage set as the entry conditions were generated based on recent cost-earnings studies on the Hawaii fishery. Thus, several micro-level entry conditions, which are used to approximate the decisions at the fishermen's level, are incorporated in the current model. The detailed discussions on the three sets of entry conditions are presented in the following paragraphs.

2.5.1 Trip Entry Condition

First, fishermen make the decision whether to enter into fishing operation for each production period. The appropriate time span for the short-run production process of fishing vessel is the length of a fishing trip (Doll 1988). Just as a farmer commits resources prior to and during a production cycle, a fisherman inputs resources and makes production decisions prior to and

Commercial fleets' trip entry condition. For commercial fleets, a trip is feasible if revenue gained at least covers operating costs. A trip entry condition was incorporated into the model to ensure that commercial fishermen at least cover trip expenses.

$$N_{ijkl}E_{ijkl} \geq 0 \tag{7}$$
$$N_{ijkl} = \sum_{s}\left(p_{ils}d^{f}_{ijkl}R_{ijkls}\right) - c_{ijkl}$$

where:

Variables:

N_{ijkl}: trip net revenue (\$/trip);
R_{ijkls}: catch per fishing day of species s for fleet i targeting species j in area k during season l (lb/trip);

Parameters:

p_{ils}: fish price for species s caught by fleet i during season l (\$/lb);
d^{f}_{ijkl}: number of fishing days per trip for trip E_{ijkl} (days/trip);
c_{ijkl}: variable costs (trip costs) per day for trip E_{ijkl} (\$/trip);

Therefore, a trip (E_{ijkl}) is possible only if the trip net revenue (N_{ijkl}) is greater than or equal to zero. Equation (7) implies that positive E_{ijkl} requires a non-zero net revenue which implies the following condition:

$$E_{ijkl}\begin{cases} \geq 0 & \text{if } N_{ijkl} \geq 0 \\ = 0 & \text{if } N_{ijkl} < 0 \end{cases}$$

Net return of a trip is a variable related to total catch of a trip, fish prices, and the trip's variable costs. Total catch of a trip depends on CPUE (catch per fishing day of targeted species and bycatch R_{ijkls}) and the trip fishing days (d_{ijkl}). Because the major variables of fish prices in Hawaii's fresh-fish market depend on fish species, fish size, fish harvesting method, and fish quality grade (Bartram *et al.* 1996), fish prices (p_{ils}) were assumed to vary by fleet, season, and species. Excluding handling fees, prices received by fishermen (p_{ils}) were approximately 90% of ex-vessel value. In the equation of the trip net return (N_{ijkl}), prices that fishermen received were used to calculate trip revenues of fishermen.

Trip costs (c_{ijkl}) contain three components: operating costs, traveling costs, and turn-around (the time to unload catch and get supplies for another fishing trip) costs. Trip costs are computed as:

$$c_{ijkl} = c^{t}_{i}d^{t}_{ik} + c^{f}_{ij}d^{f}_{ijkl} + c^{r}_{i}d^{r}_{ij}$$

where:

c^{t}_{i}: costs per traveling day, assumed to vary by fleet (i), refers mainly to fuel, oil, ice, and foods for crew.
c^{f}_{ij}: costs per fishing day, assumed to vary by fleet (i) and target (j), refers mainly to travel costs and bait.

c_i^r: costs per turn around day, assumed to vary by fleet (i), refers mainly to mooring fee.

d_{ik}^t: number of trip traveling days, assumed to vary by fleet (i) and area (k), because different fleets may travel at different speed to different areas;

d_{ij}^r: necessary turn-around days between trips, assumed to vary by fleet (i) and target (j), refers to the time spent for unloading fish, replenishing for the next trips, and rests or breaks for the fishermen. For commercial fishermen, d_{ij}^r depends on trip length (days at sea). The longer the trip length, the longer the time for fishermen to unload fish, replenish goods and supplies and rest. For recreational fishermen who usually fish on weekend, the turn-around day (the break time between trips) is their work-time on weekdays.

d_{ik}^t: number of fishing days in a trip, assumed to vary by fleet (i), target (j), area (k), and season(l). Since the number of traveling days is relatively fixed, trip length primarily depends on the number of fishing days. The number of fishing days is generally affected by the shelf-life of fish, vessel capacity, and motivations of fishermen. In Hawaii, fishermen who target tuna for the 'sashimi' (raw fish) market fish less days than the fishermen who target swordfish, which usually is processed and sold as a frozen product, do. Recreational fishermen usually take shorter trips than commercial fishermen do (Hamm and Lum 1992). Small-boat fishermen who sell at least part of their catch usually had 42% longer trip length than that of fishermen who did not sell any of their catch.

Recreational trip entry condition. The number of trips is used to measure the recreational experiences in the current study. Even though the non-commercial fishermen of Fleets 1 and 3 are not seeking income or profit from fishing activities, they may have to meet certain conditions in order to continue their fishing practices. Recreational fishermen may expect a certain percentage of successful fishing trips or expect a certain level of CPUE. Expense fishermen may expect a certain amount of revenue from fish sold to cover a portion of their fishing expenses. Since information on the entry conditions or motivations of the non-commercial fishermen is limited, the entry condition for recreational boats (Fleet 1) is assumed to be at least 90% of the current catch rate of the desirable species. The lower bound of the coefficient of CPUE is arbitrarily defined as 90%, and the impact of the value of the coefficient of CPUE for the recreational fishing can be examined by conducting sensitivity analyses to the model. Expense fishermen were assumed to sell about 51% of their catch, and the revenue from fish sales will cover at least 30% of the trip expenses. The entry condition of the expense fleet was based on the actual practices as reported in a recent study by Hamilton and Huffman (1997).

The trip entry conditions of Fleet 1 and Fleet 3 are expressed mathematically as follows:

$$\left(A_{ils} - 0.9\right)E_{ijkl} \geq 0 \qquad i = 1 \qquad (8)$$

$$\left[0.51\sum_{s}\left(p_{ils}d_{ijkl}^{f}R_{ijkls}\right) - 0.3c_{ijkl}\right]E_{ijkl} \geq 0 \quad i = 3 \qquad (9)$$

where:

Variables:

A_{ils}: CPUE coefficients;

E_{ijkl}: number of trips of fleet i target j in area k during season l (trips).

Parameters:

p_{ils}: fish price for species s caught by fleet i during season l ($/lb);

d^{f}_{ijkl}: number of fishing days for trip E_{ijkl} (days/trip);

c_{ijkl}: trip costs for trip E_{ijkl} ($/trip).

2.5.2 Owner's Entry Condition

The owner entry condition is specified only for commercial fleets and ensures that an owner's return adequately covers their investment in the long-run. Because most of the owner's expenses were fixed on an annual basis, the owner entry condition specifies that annual owner net income should be greater or equal to the fixed costs.

$$\left(\sum_{j}\sum_{k}\sum_{k}(1-\alpha_i)N_{ijkl}E_{ijkl} - fc_iV_i\right)V_i \geq 0 \qquad (10)$$

where

Variables:

N_{ijkl}: trip net revenue by fleet i target j in area k during season l ($/trip);

E_{ijkl}: number of trips of fleet i target j in area k during season l (trips);

V_i: number of vessels in fleet i (vessels);.

Parameters:

α_i: crew share of net revenue for fleet i;

$(1\text{-}\alpha_i)$: owner share of net revenue for fleet i;

fc_i: fixed costs, include opportunity costs of investment, depreciation, maintenance, and insurance ($/year).

Therefore, a fleet (V_i) is feasible only if the annual income to owner is greater than or equal to the annual fixed costs. Thus, equation (10) implies the following condition:

$$V_i \begin{cases} \geq 0 \; if \left(\sum_{j}\sum_{k}\sum_{l}(1-\alpha_i)N_{ijkl}E_{ijkl} - fc_iV_i\right) \geq 0 \\ = 0 \; if \left(\sum_{j}\sum_{k}\sum_{l}(1-\alpha_i)N_{ijkl}E_{ijkl} - fc_iV_i\right) < 0 \end{cases}$$

2.5.3 Crew's Entry Condition

The crew (including captain) expects certain income from fishery otherwise they may switch to other types of employment. Thus, the crew entry condition is included in the model to ensure that the crew income is sufficient to attract crew members to engage in the fishery. The crew entry conditions for commercial fleets are specified on an annual basis and is expressed mathematically in the following equation:

$$\left(\sum_{j}\sum_{k}\sum_{l}\alpha_i N_{ijkl}E_{ijkl} - \omega_i\left(d^f_{ijkl} + d^t_{ik}\right)E_{ijkl}\right)V_i \geq 0 \tag{11}$$

where:

Variables:

N_{ijkl}: trip net revenue by fleet i target j in area k during season l ($/trip);
E_{ijkl}: number of trips of fleet i target j in area k during season l (trips);
V_i: number of vessels in fleet i (vessels).

Parameters:

ω_i: expected wage per working day (day at sea) for all crew member of a vessel in fleet i ($/day);
$d^f_{ijkl} + d^t_{ik}$: trip length (days at sea) for trip E_{ijkl} (days/trip);
α_i: crew share of net revenue for fleet i.

The crew's satisfaction with their income does not imply that the owner breaks even from the fishing operations. Therefore, a commercial fleet is economically feasible on an annual basis only if both crew and owner entry conditions are satisfied. With entry conditions, the optimal level of effort may not be consistent with the optimal level of effort without considering entry conditions (Pan 1998).

2.6 Objective Functions

Objective functions are essential components of mathematical programming models. They are based on the policy goals of decision-makers. A multiobjective programming model attempts to optimize two or more objective functions simultaneously to search for a *Pareto optimal* solution for a multiobjective optimizing problem. The number of objective functions incorporated into a multiobjective programming model depends on the needs of the research problem and the availability of the information on the specific problem. The choice of multiobjective programming techniques depends on the number of objective functions and the availability of relative preferences on the objective functions (Romero and Rehman 1989).

The policy goals for managing Hawaii's fisheries are designated primarily by a single entity: Western Pacific Regional Fishery Management Council (WPRFMC), the authority for managing EEZ (exclusive economic zone) fisheries in Hawaii. The main task of the Council is to protect fishery resources while maintaining opportunities for domestic commercial and recreational fishing at sustainable levels of effort and yield (WPRFMC 1998). Since fisheries management is typically characterized by multiple and often conflicting objectives, the analytic hierarchy process (AHP) was applied to evaluate and weigh the Council's management goals among a variety of Council groups (Leung *et al.* 1998). This study found that the biological criterion, among the four high-level goals: biological, economic, social, and political, had the highest priority (0.526). The economic and social criteria were of roughly equal weights (0.191 and priority (0.526). The economic and social criteria were of roughly equal weights (0.191 and 0.20). The AHP study also indicated the conservation goal (biological criterion) is a particularly important goal from the view of the Council members whose average weight on the biological criterion is 0.714. In addition, a series of sub-criteria for each of the four high-level goals (biological, economic, social, and political goals) was identified for the Hawaii fisheries management in the AHP study (Leung *et al.* 1998).

Conservation is an essential goal of the fisheries management in Hawaii (WPRFMC 1998, and Leung *et al.* 1998). In current model, the conservation goal (to protect fishery resources) is incorporated into the model by specifying the stock constraints (the total available catch constraints).

To evaluate the tradeoffs between commercial and non-commercial (including recreational and traditional subsistence) fishing, the study constructs a two-objective model. The two objectives considered in this study are stated as 1) maximizing fleetwide profit; and 2) maximizing recreational (or non-commercial) trips which includes the traditional fishing trips from both the recreational fleet and the expense fleet.

Profit maximization is a behavioral assumption underlying any commercial activities based on economic theory. Therefore, the value of commercial fishing is presented by fleet-wide profit in this study. The fleet-wide profit is defined here as the total annual fleet net revenue that is derived by subtracting trip variable costs, expected crew income (representing the shadow price of labor), and fixed charges from the gross annual fleet revenue. Thus, fleet-wide profit represents precisely the economic rents of the entire fishery if all their inputs are valued at their shadow costs and their outputs are valued at their margins. Since stock effect is not included in the current model, the shadow price of the foregone fish resource appears to zero in this case.

Placing a value on non-commercial fishing (recreational and traditional subsistence fishing) involves complicated theoretical and philosophical concerns. In this study, the value of non-commercial fishing is measured by the total amount of participation, that is the number of fishing trips taken by the recreational and traditional subsistence fishermen.

Several approaches are available to formulate and solve multiobjective programming models. Since only two objective functions are included in the current study, the tradeoff between these two objectives can be traced using the noninferior set estimation (NISE) method (Cohon *et al.* 1979). The NISE method is the most effective technique to solve two objective problems but it can be applied to two-objective models, while the other multiobjective programming techniques, such as goal programming and compromise programming, are capable of solving multiobjective models with more than two objectives (Romero and Rehman 1989). The two objectives are formulated in the mathematical equations below:

Maximize fleet-wide profit:

$$Max \sum_i \sum_j \sum_k \sum_l \sum_s N_{ijkl} E_{ijkl} - \sum_i \sum_j \sum_k \sum_l \omega_i (d^f_{ijkl} + d^l_{ik}) E_{ijkl} - \sum_i fc_i V_i \qquad \text{for i = 2, 4, to 9}$$

Maximize number of recreational trips:

$$Max \sum_i \sum_j \sum_k \sum_l E_{ijkl} \qquad \text{for i = 1, 3}$$